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THE MATHEMATICAL MODEL APPLIED TO SOLIDIFY AND SEGREGATION OF LEDEBURITE TOOL STEEL INGOTS

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Abstract. *In order to determine the optimum geometry of the ingot mold format (the format of ingot mold with a diameter per height ratio H / D <3 and the conicity of minimum 7%) was analyzed by mathematical modeling of solidification and segregation of the carbon and sulfur in it.*

It was considered 205Cr115 steel type (according with , STAS 3611 - Romanian stardandization) and known also as X210Cr12 steel type (according with European standard). It has been considered an element of volume of coordinates x, y, z in the solidifying ingot and have made the following assumptions: (i) the equilibrium distribution ratio K, is applied to the solid-liquid interface; (ii) solid diffusion is negligible during solidification; and (iii) the solid density is constant during solidification. In carrying out the simulation of segregation mechanisms are resolved heat transfer equation, that simulating the solidification process and are are solved the interdendritic fluid equation of motion.

Keywords: *X210Cr12, solidification mathematical model, ledeburite tool steel ingots*

1. INTRODUCTION

Tool steels quality is evaluated by how the tool behaves under conditions of use. Tool steel should have those technical characterisitcs that assure maximum reliability, even if their production causes some difficulties in manufacturing technology. The main characteristics that determine the behavior of the service tool are hardness and toughness, both related to the chemical composition, size and distribution of carbides, depens also of grain size and degree of purity[1-4]. The steel purity is assured by the way of elaboration process (oxidation, deoxidation), steel evacuation and casting of steel. The quality of the carbides is based, first of all, on the chemical composition of steel and of a number of technological factors, such as: (a) the conditions of casting and solidification, (b) plastic deformation and (c) heat treatmen, which more or less influence the homogeneity. In the segregation process it has an important role the physico-chemical charactistics of policomponent system (the alloy tool steel). Each steel grade having its own solidification characteristics and even in the same type of steel are differences depending on the carbon content)[1, 2].

Thus, at the solidification process appear at a time the α, H, phases, carbides, the areas of occurrence of each phase and their coexistence with the liquid being very different.

Taking into account the starting pouring temperature and the early change starting solidification temperature (separation of carbides and the extent of different temperature areas on the different phases) resulting importance of respecting the conditions of casting, for the quality of carbides: the temperature and speed casting, the characteristics of the mold, the cooling conditions.

It is known that the casting temperature is increasing influence on the re-melting and, consequently, the removal, and the degree of segregation and the size of the primary carbides In the following table (Table 1) shows the dimensional characteristics of steel ingot mould used for casting of ledeburite tool steel ingots:

Table 1. Dimensional characteristics of ingot mould

Steel Grade	Product Diameter	Ingot Type	Dimensional characteristics of ingot mould			
			Side [mm]	Height [mm]	H/D	Wall Thickness [mm]
Ledeburite tool steel	< 80 mm	254 mm 300kg	310/ 225	710	2.52	65 /72
	< 150mm	356 mm 1050 kg	425/ 314	1258	3.40	90/ 96

The size of the ingot has a great influence on the size of the network of carbides, in particular with respect to its homogeneity of the ingot section, as shown in Fig. 1.
Studies on ingot less than 300 kg, used in ledeburite steel casting have shown that the best results on the ingot axial capacity is obtained when using ingots with H / D <3 and conicity less than 7% [1].

Ingot mold wall thickness is also a much-discussed parameter. Reducing mold wall thickness and degree of homogeneity favorable influence the structural homogenity degree due segregation carbides.

An ingot mold with thick walls provide intense cooling during the crust formation the ingot, after that, begins to constitute an impediment to the heat flow outward, reducing cooling intensity.

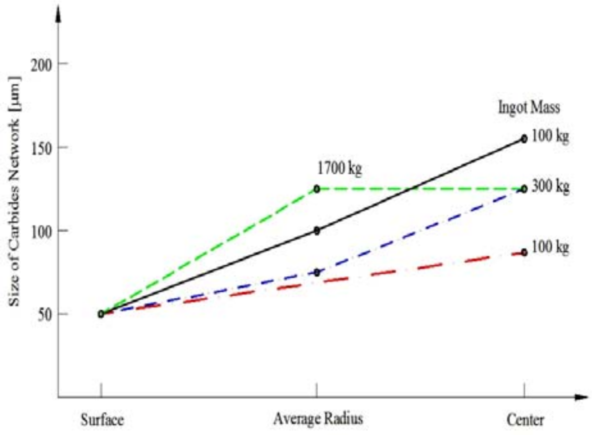

Figure 1. The size of the network of carbides, in correlation with ingot section

2. MATHEMATICAL MODEL FOR SOLIDIFICATION AND SEGREGATION OF SOLID STEEL INGOTS

Improvement of the existing ingot formats in operating process, is a part of the general issue on reducing material consumption. In literature was developed different models of solidification of metals [5-9] taking into account the heat exchange by conduction and convection heat exchange, but with insufficient evaluation of the influence of convective heat transfer on the evolution of the solidification front.

In order to determine the optimum geometry of the ingot mold consisting of G10 m type, was analyzed, by mathematical modeling, the solidification process and the carbon and sulfur segregation, and also, in parallel, the same calculations were performed for the format G10 used in Electric Steelworks Department of the former Special Steel Plant (COS Târgovişte Company).
It was considered the 205Cr115 steel grade.

The mechanism of solidification and segregation of solid steel ingot can be treated by modeling hydrodynamic behavior of the interdendritic fluid due (i) to shrinkage forces occurring during solidification and due (ii) the forces of gravity caused by differences in density of the fluid.
Liquid bicomponent phases region is considered as a porous medium, where the porosity coefficient and the pores' size depends on the size of the solidification pits fraction and solid fraction.The liquid bicomponent phases region is changing during solidification.
We consider a volume element of x, y, z coordinations in the solidifying ingot and the following simplifying assumptions are made:
- Equilibrium distribution ratio K is applied to solid-liquid interface;
- Solid diffusion is negligible during solidification;
- Density of the solid is constant during solidification.
Under these conditions, the equation describing the local redistribution of the solution is:

$$\frac{\partial g_L}{\partial C_L} = \frac{1-\beta}{1-K}\cdot\left(1+\frac{\bar{v}\cdot v\cdot T}{\varepsilon}\right)\cdot\frac{g_L}{C_L} \qquad (1)$$

where: $\frac{\partial g_L}{\partial C_L}$ is the differential variation of the volume fraction of liquid gL with the concentration in the liquid C_L, considered relative to the volume element;
β is the solidification shrinkage coefficient that is considered as a function of temperature;
K is the equilibrium distribution coefficient which is a function of temperature;
ε is change rate of the temperature in the volume element (degrees ° C / S)
$\bar{V}$ is the interdendritic fluid velocity in comparison to the solid (cm / s).
Through the integrationof equation (1), and setting boundary conditions C0 and CL is obtained:

$$C_L = C_0\cdot g_L^{-1} / \left(\frac{1-\beta}{1-K}\right)\cdot\left(1+\frac{\bar{v}\cdot v\cdot T}{\varepsilon}\right) \qquad (2)$$

Where C_0 is the initial concentration
So, the distribution of the liquid phase concentration values in ingot it depends, at any time, of time.
In the course of the simulation of the mechanism of segregation are solved the following equation:

A. The heat transfer equation, is the equation that simulating the solidification process:

$$\frac{\partial T}{\partial \tau} = -\frac{\lambda}{C_P\cdot\rho}\cdot\bar{v}\cdot v\cdot T \qquad (3)$$

where: T - temperature, ° C;
τ- time, s;
λ - thermal conductivity, cal / cm-s- ° C;
CP Specific heat; cal / g- ° C;
ρ-density, g / cm3

B. The equation of the liquid fraction is:

$$f_L = \frac{g_L\cdot(1-\beta)}{1-\beta\cdot g_L}\cdot \qquad (4)$$

where G_L is the liquid fraction by weight.

C. The equation of motion of the interdendritic fluid:

$$v = -\frac{K}{\mu \cdot g_L}(\overline{v}_p + g_L \cdot \overline{g}_n) \qquad (5)$$

where:
μ - interdendritic viscosity; $\mu = f(T)$ g / cm $^{-s}$;
K - fluid permeability of the structure considered as $K = f(g_L)$ cm^2;
$\overline{g}_n$ - The acceleration vector of gravity, cm / s^2;
$\overline{V}_p$ - pressure, kgf / cm^2.

Solving the equation of heat transfer and interdendritic fluid movement is done using the finite element method.

This method analyzes the sudied field in the following three steps:
(a) dividing the field into a finite number of small discrete elements and interrelated by a finite number of nodes;
(b) analysis of the properties of each element to suit the phasic area in which it replaces; calculate the "stiffness" of each element using the principle of minimizing the potential energy of the system;
(c) analysis of the distribution elements and reassembly of the physical variables of the contour determined by the condition data (specified).

By solving the heat transfer equation is determined, at each time, until solidification:
- gradient temperature distribution in the ingot;
- distribution of the temperature change rates in ingot

Knowing the temperature distribution in the ingot, we can calculate the values of physical parameters of mathematical model: the thermal conductivity; the density; viscosity; permeability; electrical constants.

Thermodynamic and thermophysical quantities that are dependent on temperature, to solidification steel can be determined using the relationship [8-12]:

$$\rho_{(T)} = 7840\frac{1}{1+\alpha(T)\cdot(T-T_0)} \qquad (6)$$

where:

$$\alpha_{(T)}10^6 = 10{,}7 + 0{,}6\left(\frac{T-273{,}16}{100}\right) - \frac{2{,}9}{ch\left[0{,}76\left(\frac{T-T_0}{100}\right)^2\right]}$$

T_0=1178,16K

For T <1041K, Cp (T) is calculated with the equation

$$C_p(T) = 1000\left[0{,}4814 + 0{,}1997\left(\frac{T-273{,}16}{100}\right) + 0{,}812\cdot e^{-0{,}0099(1041-T)}\right] \qquad (7)$$

For T >1041K, Cp (T) is calculated with the equation:

$$C_p(T) = 1000\left[0{,}4814 + 0{,}1997\left(\frac{T-273{,}16}{100}\right) + 0{,}812\cdot e^{-0{,}0261(1041-T)}\right] \qquad (8)$$

For $T \le 1173$K, $\lambda(T)$ is calculated by the formula::

$$\lambda(T) = 26.74 + \frac{(\lambda_0 - 26{,}74)(1173{,}16 - T)}{1173} \qquad (9)$$

where:

$$\lambda_0 = 74{,}42 - 16{,}28[\%C] - 34{,}88[\%Si] - 23{,}36[\%Mn], \qquad (10)$$

For T > 1173K,
$\lambda(T)$ is calculated by the formula:

$$\lambda(T) = 0{,}01164\cdot T + 13{,}08628 \qquad (11$$

For the calculation of thermophysical quantities that vary with temperature and are input data, you can use the following relations:

$$C_p = (23{,}57 + 9{,}75T\cdot 10^{-3})4{,}826 \qquad (12)$$

$$\rho_l = [10{,}678 - 13{,}17\cdot 10^{-4}(T_l - T_s)]\cdot 10^3 \qquad (13)$$

where :
- C_p is the heat capacity ;
- ρ_l is the density of the liquid;
- ρ_s is the solid density;
- λ the thermal diffusivity of the alloy in solid form;
- λ_0 the initial thermal conductivity;
- T_l the liquid alloy temperature;
- Ts the temperature of solidification;

By solving the motion equation of interdendritic fluid is determined, in every time, the biphasic zone:
- Distribution of the fluid movements in the biphasic zone ont the all three directions;
- Stress distribution in the biphasic dendritic structure;
- Interdendritic fluid velocity distribution.

We take into account two formats of the ingot moulds: G10 used in COS – Targoviste SA (Electric Steelworks Department of the former Special Steel Plant , COS Târgoviste Company) and G10M with the following parameters and features:

Table 2. Ingot format moulds used at COST S.A.

G10M Ingot format mold	Mass [Kg]	Dimensions [mm]				
		D_{sup}	D_{inf}	D_{med}	H_{mas}	H_{tot}
	980	420	320	370	200	1310
	Mass [Kg]	Volume [dm^3]			Conicity [%]	
		V_1	V_2	V_{mass}		
	980	123.5	19.0	13.3	9.9	

where
D_{sup}- the upper diameter of ingot mould;
D_{inf} - the lower diameter of ingot mould;
D_{med} - average diameter of ingot mould;
H_{mas}- height of the ingot crop end (shrinking head);
H_{tot}- total height (the ingot crop end /shrinking head+ ingot mould);
V_1- volume of ingot mould;
V_2- volume of the ingot crop end (shrinking head).

3. CONCLUSIONS

The test results using the mathematical model are following:

(i) the axial biphasic area that solidifies the last in ingot and where the solidification shrinkage gap('pipe') in ingot is formed, it is positioned all in the ingot crop end (shrinking head) for the 205Cr115 steel type;

(ii) The maximum amount of carbon segregation, express by the maximum segregation coefficient, it's less for the G10 format in comparison with G10 m format.

(iii) the maximum content of carbon in the area with maximum segregation match in the required field of composition for this steel grade.

In conclusion, the format ingot proposed is G10m that was dimensioned according with indications from the literature, that ensures appropriate quality of the ingots. The obtained segregation value of C is in less than similar value of ingot G10 type.

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