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Numerical Model for Solidification Zones Selection in the Large Ingots

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Abstract

A vertical cut at the mid-depth of the 15-ton forging steel ingot has been performed by curtesy of the CELSA – Huta Ostrowiec plant. Some metallographic studies were able to reveal not only the chilled undersized grains under the ingot surface but columnar grains and large equiaxed grains as well. Additionally, the structural zone within which the competition between columnar and equiaxed structure formation was confirmed by metallography study, was also revealed. Therefore, it seemed justified to reproduce some of the observed structural zones by means of numerical calculation of the temperature field. The formation of the chilled grains zone is the result of unconstrained rapid solidification and was not subject of simulation. Contrary to the equiaxed structure formation, the columnar structure or columnar branched structure formation occurs under steep thermal gradient. Thus, the performed simulation is able to separate both discussed structural zones and indicate their localization along the ingot radius as well as their appearance in term of solidification time.

Keywords: Theory of crystallizations, Thermal gradient field, Constrained solidification, Unconstrained solidification

1. Introduction

A fundamental work dealing with solidification zone selection is the model associated with the characteristic behavior of the solid/liquid interface undercooling, [1]. The theory was developed by considering the convection and its effect on segregation, [2]. Generally, competition between constrained and unconstrained solidification is the driving force for the formation of different structural zones in the ingot, [3]-[7]. Usually, the temperature field formation is subjected to the detailed analysis, [8]-[13]. However, the thermal gradients field simulation in an ingot seems to be most accurate method for the zones selection, [14]. The thermal gradient field simulation is preceded by calculation of temperature field, [15], [16]. A proper mode of temperature into thermal gradient field transformation is to be applied, [17].

2. Reproduction of the Ingot's Zones

Experimental observations of the steel morphology were made due to the vertical cut at the mid-depth of the 15-ton forging steel ingot. Some samples were selected along the ingot radius to reveal solidification zones which are identified by the presence of equiaxed or columnar grains, respectively, Fig. 1. The discussed solidification zones are directly connected with the temperature field or, more precisely, with the global thermal gradient, Fig. 2.

The global thermal gradient is positive but steep for columnar structure formation. This global thermal gradient is equal to local thermal gradient which is observed at the solid/liquid (s/l) interface. On the other hand, the global thermal gradient is positive but moderate for equiaxed structure appearance. The local thermal gradient is negative and differs from the global one.
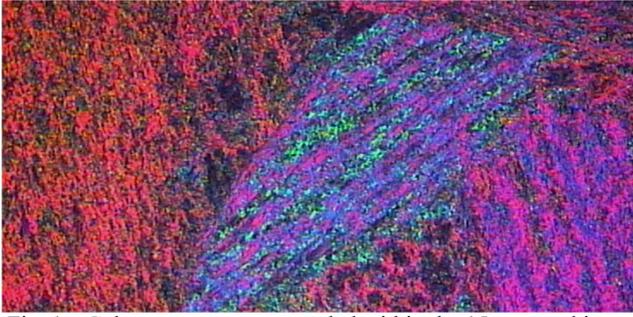
Fig. 1a. Columnar structure revealed within the 15-ton steel ingot

Fig. 1b. Equiaxed structure revealed within the 15-ton steel ingot
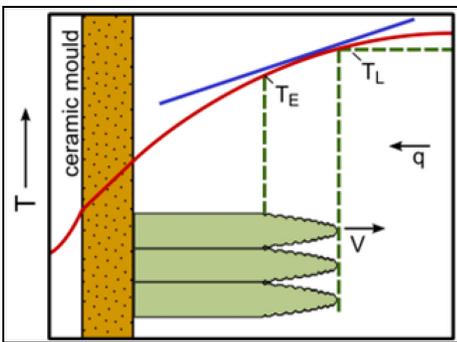
Fig. 2a. Steep thermal gradient (blue line) proper for the columnar grains formation (directional growth); T_E - eutectic temperature; T_L - liquidus isotherm; v - growth direction; $\bar{q}$ - direction of heat transfer; R_1, R_2 - ingot radiuses; T - temperature
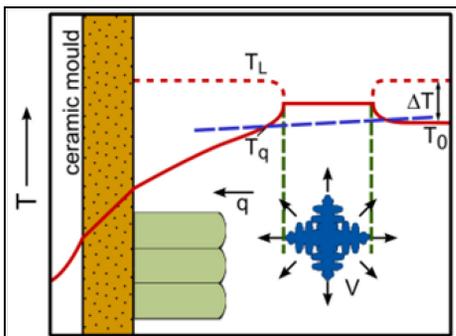
Fig. 2b. Moderate thermal gradient (blue line) adequate for the equiaxed grains formation; ΔT - undercooling of the liquid; T_q - temperature field in the solid; T_0 - temperature filed in the liquid

2.1. Temperature Field Simulation

The geometry of both ingot and mold was imposed to the calculation of the temperature field. The *Abaqus Software* applied to simulation was based on the Green-Naghdi basic energy balance, [18]:

$$\int_V \rho \, \dot{U} \, dV = \int_S q \, dS + \int_V \sigma \, dV \tag{1}$$

$$f = -\lambda \frac{\partial T}{\partial z} \tag{2}$$

where ρ is the density; U- internal energy of the s/l system; V- volume of the solid; S- surface area; q- heat flux per unit area of the body; σ- heat supplied internally into the body per unit volume; f- heat flux; λ- conductivity matrix; z- position.

The performed simulation had a general character and was not dealing with all structural zones which can be revealed in a large ingot, Fig. 3. First of all, the current mode of solidification zones' selection is associated with the columnar into equiaxed structure transition zone due to temperature field simulation, Fig. 4 and confirmed by the subsequent calculation of the thermal gradients' field.
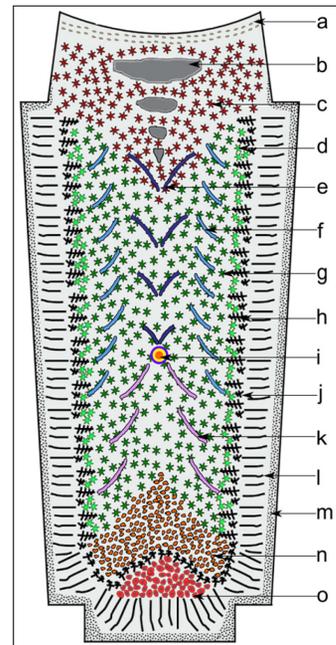
Fig. 3. Outlined structures in a large steel ingot; a) exothermic hot topping compound; b) shrinkage cavity; c) equiaxed grains; d) equiaxed grains formed inside the $C{\rightarrow}E$ transition zone; e) "V" – segregates; f) primary "A" segregates; g) equiaxed grains in the ingot core; h) columnar branched grains; i) supposed position of the so-called "switching point" for the "A" into "V" conversion; j) layer of the columnar branched grains formed before the $C{\rightarrow}E$ transition; k) secondary "A" segregates; l) columnar grains; m) chilled equiaxed grains; n) upper sedimentary cone; o) first sedimentary cone with some inclusions embedded in austenite
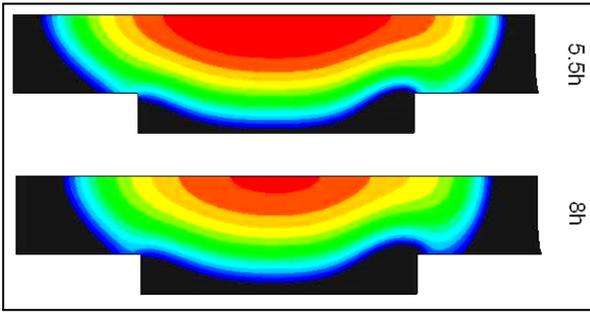
Fig. 4. Temperature field calculated for simplified geometry of an ingot

2.2. Thermal Gradients' Field Analysis

The results of the temperature field simulation allowed for the calculation of the thermal gradient field. Especially, the thermal gradient at the solid/liquid interface has the significance for the analysis carried out. Therefore, the temperature field was studied at the s/l interface but by the side of the liquid. Approximation of the $\partial T/\partial R$- gradient for each unit of the mesh was performed by the calculations of the ratio between both differences: $\Delta T/\Delta R$, where R is the ingot radius.
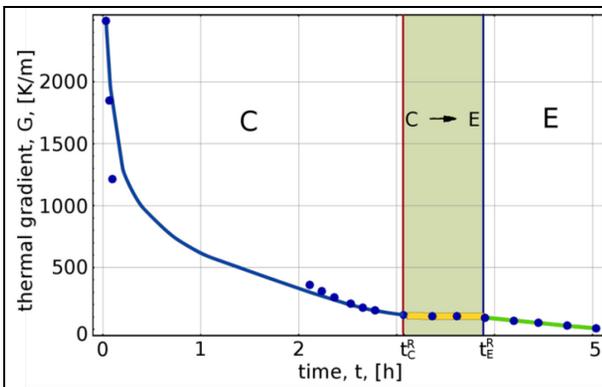
Fig. 5a. Localization (in time) of the $C{\rightarrow}E$ - transition for the 0.1 [m] - virtual thickness of the mould as applied in simulation
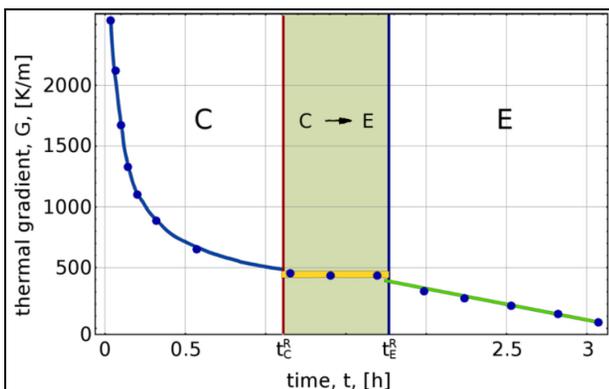
Fig. 5b. Localization (in time) of the $C{\rightarrow}E$ - transition for the 1.0 [m] - virtual thickness of the mould as applied in simulation
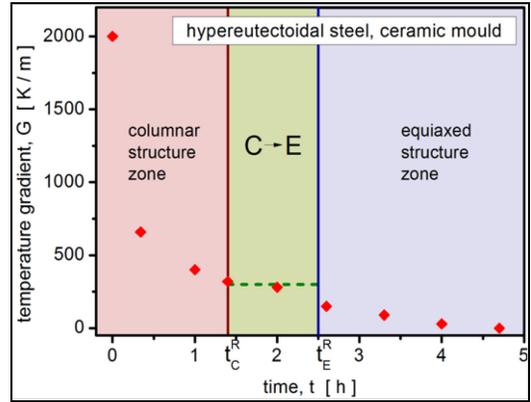
Fig. 5c. Localization (in time) of the $C{\rightarrow}E$ - transition for the optimal thickness of the mould applied in the industry condition

2.3. Zones' Appearing / Disappearing

The analysis of the temperature field allows for comparing the *liquidus* isotherm motion with the s/l interface movement, Fig. 6. Mathematics of the comparison allows to formulate the equations:

$$v_C(t) = v(t_{EC}) - 0.012\, t^{2.23} \qquad t \in \left[t_{EC}, t_E^R \right] \tag{3}$$

$$v_E(t) = 0.06 / \left(1 + \exp\left(-5.54\left(t - 1.78 \right) \right) \right) \qquad t \in \left[t_C^R, t_{max} \right] \tag{4}$$
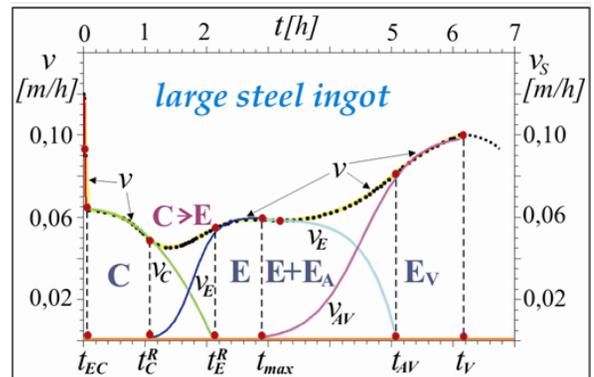
Fig. 6. Mathematics of the appearance/disappearance of structural zones in a solidifying steel ingot; ν- rate of the liquidus isotherm motion;v_S=v_C; v_E; v_{AV} - s/l interface rate for columnar / equiaxed solidification and for "A" and "V" segregates formation; t_{EC}- time of the chilled equiaxed into columnar structure transition $E{\rightarrow}C$; t_C^R- time of the equiaxed structure birth; t_E^R - time of the columnar structure death; t_{max}- time of the "A" – segregates appearance; t_{AV}- "switching point"; t_V- time of the beginning of the "V" – segregates vanishing; $C{\rightarrow}E$ - the CE transition, [17]

3. Concluding Remarks

Structural zones after solidification of the 15-ton forging steel ingot have been successfully revealed. The revealed zones were:

chilled fine equiaxed grains (just under the ingot surface), columnar cells, columnar and equiaxed co-existence zone and area of the equiaxed dendrites localized around the ingot vertical axis.

The temperature field simulation allowed for initial suggesting of columnar structure disappearing, equiaxed dendrites appearing and columnar into equiaxed transition (CET) localization in term of solidification time.

The performed transformation of the temperature field into thermal gradient field lead not only to the final confirmation of the above zones localizations in function of solidification time but against the ingot radius as well. Additionally, the simulations of the thermal gradient fields were performed for two virtual thicknesses of the mould. It allowed to illustrate the effect of the heat accumulation in the mould on the CET appearance in time. This kind of simulation has a practical significance for technologists who design the mould and the solidification process in the whole. It is important because the CET localization decides on the final properties of the forging steel ingot assigned to the production of the crankshafts for the ship engines. In fact, the contribution of the columnar structure in the ingot being the result of the directional solidification has the fundamental effect on further plastic deformation o the ingot as it was discussed on the basis of directional growth observed in a laboratory condition, [19].

The analysis of the competition between liquidus isotherm movement juxtaposed by the s/l interface displacement, Fig. 6, delivers more details about the phenomena which occur during the ingot solidification. Especially fruitful was the analysis of the points of inflection visible on the v - curve. It allowed to show the ECT localization (t_{EC}- time), the so-called switching point for "A" – segregates into "V" – segregates transition, (t_{AV}- time), or the beginning of the "V" – segregates vanishing, (t_V- time). Also the CE - transition is revealed in the discussed analysis, Fig. 6.

Acknowledgements

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