International Journal of Advancements in Electronics and Electrical Engineering – IJAEEE

Volume 8 : Issue 1 - [ISSN : 2319-7498] - Publication Date: 27 Dec, 2019

Software for electron beam melting simulation

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***Abstract* — In this paper the developed software for simulation of the temperature distributions in the cast ingots at electron beam drip melting for different materials is presented. The influence of the change of the process parameters electron beam power, casting velocity and the beam radius on the temperature distributions in the cast ingot and the parameters of the molten pool can be investigated. Quasi steady-state two-dimensional heat model is implemented for the simulation of the temperature distribution in the cast ingots from different materials.**

***Keywords* — electron beam drip melting, heat model, temperature distribution, regression models, simulation software**

I. Introduction

The electron beam drip melting [1] is a classical method for processing and refining of reactive and refractory metals in vacuum. The raw material in form of bars is fed horizontally (or vertically) and drip-melted directly into the withdrawal ingot (Fig.1a). During the electron beam melting (EBM) on the surface of the molten pool, which is situated on the upper part of the cast ingot, droplets, created on the front surface of feeding rod are added. In the same time the electron beam can oscillate on the ingot surface for heating and keeping it molten. The liquid pool surface is maintained on a constant level by withdrawing the bottom of the growing ingot. Refining is based on degassing and selective evaporation of metallic and non-metallic constituents with vapor pressures higher than the base material.

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The EBM process depends on a large number of parameters, concerning the material properties and the electron beam installation processing parameters.

Heat models are used for calculation of the quasi-steady temperature distributions as an approximation at simulation of EBM [1-5]. These models are implemented for the estimation of the temperature distributions and the shapes of melted zones at electron beam melting. They are based on different assumptions for the heat source – point, linear, exponential, combined, etc. The solutions of the quasi-steady thermal physical models give approximation for the form of the temperature distributions taking into account some process and material parameters.

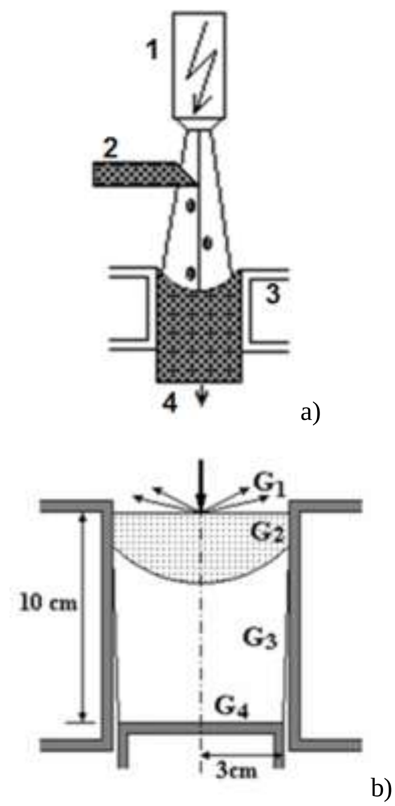

Figure 1. Electron beam drip melting a) 1 – electron gun, 2- feeding rod, 3 – water cooled crucible, 4 – ingot, b) geometrical conditions and boundary conditions: G_1 – top ingot surface, G_2 – interface molten pool/crucible, G_3 – free side ingot surface, G_4 – interface – ingot/puller.

The importance of the knowledge of the shape of the crystallization front is directly connected with the quality of the cast ingot and its crystal structure. A flat crystallization front permits formation of dendrite structures, parallel to the block axis as well as the uniform impurity displacement toward the ingot top surface (otherwise the impurities' concentration increases in the central region of the cast blocks) [1, 2].

The computer simulation of the temperature distribution at electron beam drip melting is based on the quasi steady-state two-dimensional heat model [1, 6]:

$$\frac{1}{r}*\frac{\partial}{\partial r}*\left(r*\frac{\partial T}{\partial r}\right)+\frac{\partial^2 T}{\partial z^2}+\frac{v}{a}*\frac{\partial T}{\partial z}=0\,, \qquad (1)$$

where the last term indicates the casting presented by the added heat that by the molten metal droplets falling into the crucible and given by the casting velocity of the ingot, moved with a speed v, coinciding with the z-axis. It is used an axis-symmetrical thermal geometry, coinciding with the cross-section of the casted cylindrical ingot.. The stirring and mixing processes in the molten pool are presented by a modification (increase from 1 to 2 times) of the value of the ingot thermal conductivity.

The boundary conditions take into account the radiation losses and the heating beam energy distribution with a correction of the secondary electron energy losses and they are given according the interfaces G_1, G_2, G_3 and G_4 (Fig. 1b) correspondingly:

$$\Gamma_1:\ \lambda_1\times\frac{\partial T}{\partial z}|_{z=h}=-P_n+\alpha\times\sigma\times\left(T^4-T_{st}^4\right) \qquad (2)$$

$$\Gamma_2:\ \lambda_1\times\frac{\partial T}{\partial r}|_{r=R}=\lambda_2\times\frac{\partial T'}{\partial r}|_{r=R} \qquad (3)$$

$$\Gamma_3:\ \lambda_1\times\frac{\partial T}{\partial r}|_{r=R}=-\sigma\times\sigma\times\left(T^4-T_{st}^4\right) \qquad (4)$$

$$\Gamma_4:\ \lambda_1\times\frac{\partial T}{\partial z}|_{z=0}=\lambda_2\times\frac{\partial T''}{\partial z}|_{z=0} \qquad (5)$$

where α is emissivity, σ is the Stefan- Boltzmann constant, λ is the thermal conductivity, T_{st} is the ingot surface temperature. In Table 1 are given the material characteristics, used for the calculations. The heat transfer coefficients on the boundary areas (G_1, G_2, G_4) assumed are: $\lambda_1/\lambda_{Cu}=1.0$, $\lambda_2/\lambda_{Cu}=0.8$, $\lambda_4/\lambda_{Cu}=0.8$. Working with a real process these coefficients should be estimated first in order to apply the considered here approach. The cast ingot has cylindrical axis-symmetrical form with dimensions: radius 30 mm and height 100 mm.

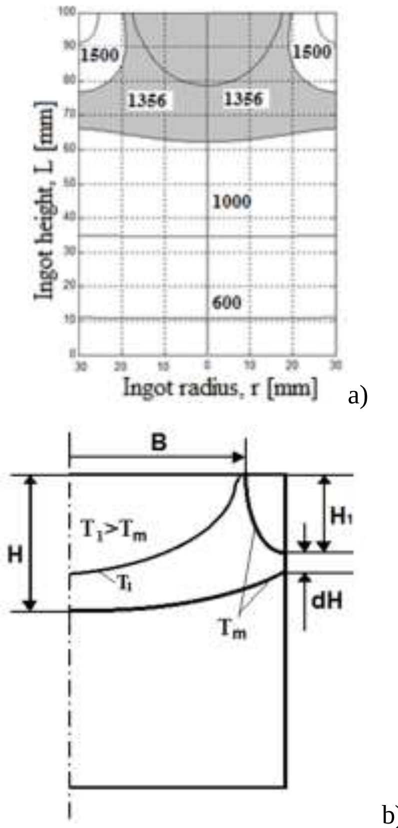

Figure 2. a) The temperature distribution at EBM in Cu ingot cross-section at input electron beam power 22 kW, radius of the beam 15 mm and crystallization speed 3 mm/min, b) Molten pool geometry parameters.

Fig. 2 presents the temperature distribution at EBM in Cu ingot cross-section at input electron beam power 22 kW, radius of the beam 15 mm and crystallization speed 3 mm/min. The colored area visualizes the molten pool area with temperatures higher than the melting temperature T_m = 1356 K. The height of the interface molten pool-crucible (G_2) is constant – 8 mm (it can become a changeable parameter in the developed software). It can be seen that below the boundary G_2, where there is a direct contact with the water-cooled crucible, a molten ring appears at certain process parameter values. This molten ring solidifies at reaching the crucible, then due to the worsened thermal contact the temperature rises and the molten ring appears again and so on. The appearance of the molten ring changes the shape of the crystallization front and is responsible for the sidewall roughness of the obtained ingots.

In this paper the developed software for simulation of the temperature distributions in the cast ingots at electron beam drip melting for different materials is presented. The influence of the change of the process parameters electron beam power, casting velocity and the beam radius on the temperature distributions in the cast ingot and the parameters of the molten pool are taken into consideration. Quasi steady-state two-dimensional heat model is implemented for the simulation of the temperature distributions in the cast ingots from different materials (copper, tantalum, tungsten). The considered performance characteristics of the molten pool geometry are (Fig. 2b): molten pool depth *H* (in the center of the ingot), the molten pool half-width *B*, the volume of the molten metal *V* in the cylindrical ingot, the height of the interface molten metal/crucible H_1 and the height of molten metal below the interface molten metal/crucible *dH* (if the molten pool has reached the outer wall of the ingot). The optimization and investigation options of the software are realized on the base of the estimated regression models for the dependencies of the molten pool characteristics on the change of the considered process parameters.

II. EBM simulation software

The developed electron beam melting simulation software gives the possibility to implement (Fig. 3):

a) the quasi steady-state two-dimensional heat model for the simulation of the temperature distributions in the cast ingots from different materials - copper, tantalum, tungsten;

b) regression models for the considered performance characteristics of the molten pool geometry.

The user can change the values of the following process parameters: electron beam power, casting velocity and the beam radius. The program can be expanded with more materials and the investigation of the influence of more process parameters.

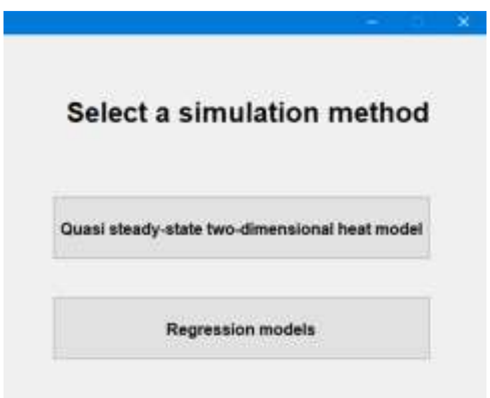

Figure 3. Starting window of the simulation software.

When the simulation of the temperature distribution in the cast ingots by quasi steady-state two-dimensional heat model is chosen, the window in Fig. 4 is opened. The choice of several parameters has to be done: the processed material and the process parameters. Then with the pushing of the start button the simulation is performed, the temperature distribution is visualized in the figure and the molten pool geometry characteristics are calculated (on the right side). The simulation stopping condition is when the temperature field does not change with more than δ = 0.001 K for two consecutive iterations.

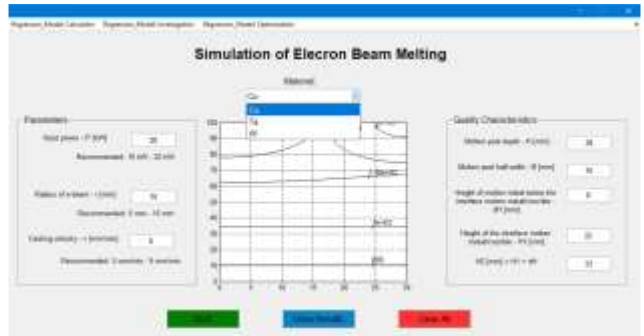

Figure 4. Simulation of the temperature distributions in the cast ingots from different materials by quasi steady-state two-dimensional heat model.

III. Calculator, investigation and optimization options

When regression models is chosen from the starting window (Fig. 3) the following three options are available:

- Calculator;
- Investigation;
- Optimization.

They are available from the menu line on each of the windows. Regression models, based on simulated experiments, are estimated for all geometry characteristics of the considered metals.

The developed software gives the possibility to explore (Fig. 5) the considered performance characteristics of the molten pool geometry. The recommended regions for choice of the process parameters (electron beam power, casting velocity and beam radius) are connected with the experimental regions for which the regression models for each material are estimated. The "Regression models: Calculator" option calculates (Fig. 2b):

- molten pool depth (in the center of the ingot) H,
- the molten pool half-width B,
- the volume of the molten metal V,
- the height of the interface molten metal/crucible H_1,
- the height of molten metal below the interface molten metal/crucible dH (if the molten pool has reached the outer wall of the ingot),
- the height $H_2 = H_1 + dH$,
- the minimum electron beam power P_{min} [6] for the appearance of a molten ring on the side-wall of the ingot.

The "Regression models: Investigation" option (Fig. 6) gives the possibility to investigate the influence of two from the three process parameters: electron beam power, casting

International Journal of Advancements in Electronics and Electrical Engineering – IJAEEE
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Volume 8 : Issue 1 - [ISSN : 2319-7498] - Publication Date: 27 Dec, 2019

velocity and beam radius, on the molten pool geometry characteristics: molten pool depth (in the center of the ingot) H, the molten pool half-width B, the height of the interface molten metal/crucible H_1 and the height of molten metal below the interface molten metal/crucible dH.

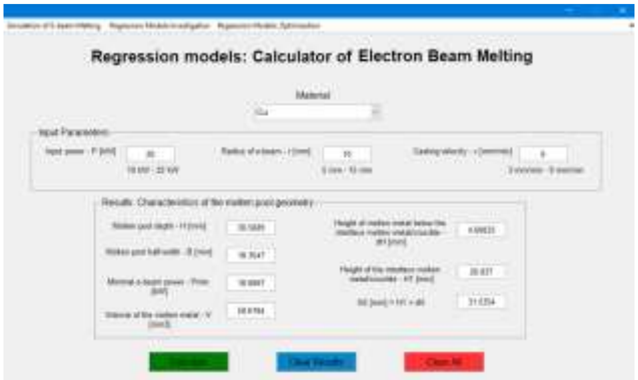

Figure 5. Regression models: Calculator

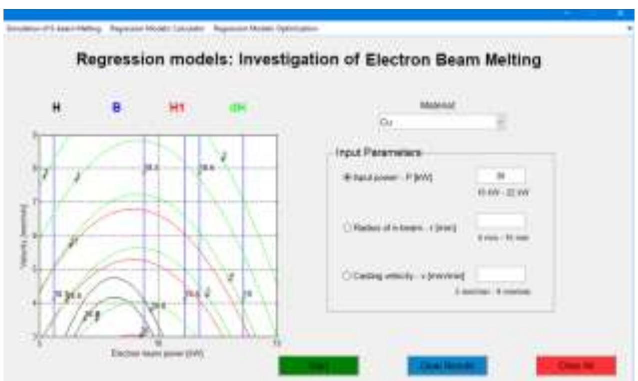

Figure 6. Regression models: Investigation

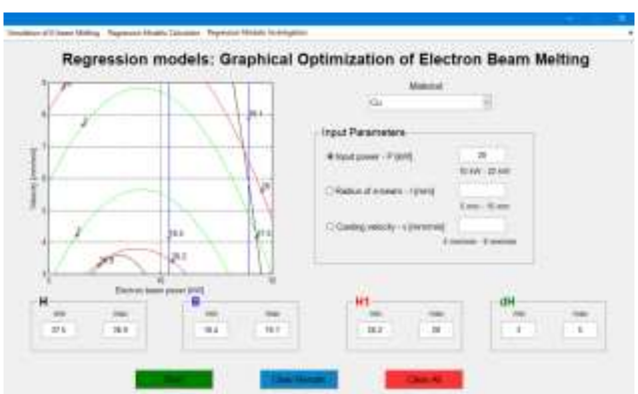

Figure 7. Regression models: Optimization

Imposed one over the other contour plots are calculated and presented for the listed characteristics, depending on two of the three process parameters. The third parameter is chosen and has a constant value within the recommended region.

The optimization of the molten pool shape is connected with the minimization of the roughness of the ingot walls, as well as obtaining more flat surface of the crystallization front, which helps the inclusions' removal toward the surface of the ingot and parallel to the ingot axis dendrite structure.

The "Regression models: Optimization" option implements a graphical multi-criterial optimization. For each of the geometry characteristics the required regions must be presented by two-sided constraints. The result is obtained graphically on the contour plot in the form of a process parameters' region, where all the requirements for the geometry characteristics are fulfilled. The contour lines present the allowable limits for each characteristic. The area cross-section of all regions is the desired solution. It is possible, that such cross-section does not exist for different values of the constant third process parameter. In such cases the desired requirements cannot be simultaneously fulfilled and the constraints should be appropriately changed.

IV. Conclusion

In this paper the developed software for simulation of the temperature distributions in the cast ingots at electron beam drip melting for different materials is presented. The influence of the change of the process parameters electron beam power, casting velocity and the beam radius on the temperature distributions in the cast ingot and the parameters of the molten pool are taken into consideration. Quasi steady-state two-dimensional heat model is implemented for the simulation of the temperature distributions in the cast ingots from different materials (copper, tantalum, tungsten). The considered performance characteristics of the molten pool geometry are: molten pool depth, the molten pool half-width, the volume of the molten metal, the height of the interface molten metal/crucible and the height of molten metal below the interface molten metal/crucible. The calculation, investigation and optimization options of the software are realized on the base of the estimated regression models for the dependencies of the molten pool characteristics on the change of the considered process parameters. The program can be expanded with more materials.

Acknowledgment

The work has been supported by the Bulgarian National Scientific Fund under contract KP-06-N27/18.

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Volume 8 : Issue 1 - [ISSN : 2319-7498] - Publication Date: 27 Dec, 2019

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