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Non-stationary heat model for electron beam melting and refining – An economic and conservative numerical method

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ABSTRACT

An economic and conservative numerical method is proposed for discretization and numerical simulation of non-stationary heat model concerning electron beam melting and refining (EBMR) of metals. The numerical model and optimization problems are developed to analyze and compare experiments and numerical data and to aid in understanding and optimizing EBMR. The axis-symmetric problem is decomposed into two locally one-dimensional problems. For the two problems, implicit and absolutely stable schemes are built for which the decomposition method gives rate of convergence of order one for both the space and time variables. The obtained discrete problems lead to linear systems of equation with three-diagonal matrixes which are solved via Thomas method. Proposition for the stability and realization of Thomas method is proved for one of the two one-dimensional problems. Criteria, related to the geometry of the crystallization front, for improvement of the quality of the obtained material after EBMR are discussed. Approaches for discretization of the criteria over the numerical solution of the model are proposed. Comparison between experimental and simulation results is made and the model is validated against liquid pool depth and diameter. Through applying the developed numerical scheme and criteria, optimization of the EBMR of copper ingots is achieved. Results for the best technological regime parameters according to the chosen criteria for the investigated ranges of the e-beam power and the beam radius are given. The results indicate that the model is able to quantitatively predict the liquid pool geometry and the optimization criteria, based on the profile, are able to propose optimal process parameters.

1. Introduction

Secondary melting and purification of reactive metals, which are extracted from ore products or recycling wastes of industrial use, pose considerable difficulties due to contamination problems caused by the refractory metal oxide pots. The increasing demand for cleanness of performed products has led to the use of water-cooled copper crucible and hearth furnaces, where the raw material is melted, refined and re-solidified without use of refractory oxide ceramic pot, typical for conventional metallurgy. The entire melting and refining operation of metals and alloys is conducted in vacuum environment using electron beams as heating source. A similar process in which plasma flows are utilized as heating sources is plasma melting (PM). The Electron Beam Drip Melting and Refining (EBDMR), EB Cold Hearth Melting (EBCHM) and Plasma Arc Cold Hearth Melting are some

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Nomenclature

T	temperature, K
H	ingot height, mm
R	ingot radius, mm
Q	height of the heat contact at G2 boundary, mm
F	total time of heat treatment, s
a	thermal diffusivity, m^2/s
ρ	density of the material, g/m^3
C_p	heat capacity, W.s/(g.K)
λ	thermal conductivity, W/(m.K)
V	casting velocity, m/s
P_b	e-beam power, W
P_{surf}	power density, W/m^2
W_v	weight loss velocity, $g/(m^2.s)$
α	metal emissivity
T_{room}	room temperature, K
λ_2	thermal conductivity of the crucible, W/(m.K)
T_{water}	mean water temperature in the water-cooling system, K
Δwall	width of the crucible side wall, mm
Δ_{under}	width of the water-cooled puller, mm
T_{melt}	melting temperature of the material, K
r_m	radius of the liquid pool, mm
d_m	diameter of the liquid pool, mm
h_m	height of the liquid pool, mm
S_m	area of the molten pool on the top surface of the ingot, mm^2
V_m	molten pool volume, mm^3
r_b	beam radius, mm
${d_m}^e$	diameter of the liquid pool, obtained from experiment, mm
${h_m}^e$	height of the liquid pool, obtained from experiment, mm
${d_m}^s$	diameter of the liquid pool, obtained from simulation, mm
${h_m}^s$	height of the liquid pool, obtained from simulation, mm
σ	Stefan-Boltzmann constant, $W/(m^2.K^4)$

of the modern technologies comparable to the conventional Vacuum Arc Remelting (VAR) technologies which are employed industrially for fabrication of refined pure metals in water-cooled crucibles and in some cases in hearth.

In the vacuum induction furnaces the cast metal is contaminated by the refractory ceramic pot material and by the adsorbed gases. Vacuum arc melting in water-cooled copper crucible had overcome this disadvantage, but independent control of melting and cast velocities is impossible. In addition, the refining time of the metal is connected to and limited by the arc power. The required purity of the performed metal could be reached only through several consecutive melting operations. Preliminary production of the compact electrodes is also required.

Recently, as a well established physics method for melting and material purification, the EBM has become a widely used technology [1–11]. In the EBM furnaces, the combination of high vacuum environment (about 10^{-4} Pa) and superheating up to 1.3–1.5 of the melting material temperature (including the refractory metals), results in a highly efficient refining process. The e-beam and the high vacuum environments provide superior refining level of gases, metals and non-metal inclusions. An additional important advantage of the EBMR process is the ability to control the heating source intensity independently of the kind of material and the cross-section dimensions of the fed material, as well as of the molten pool volume and the used crucible type. The method offers also a high degree of flexibility of the EB heat source, which becomes an important reason for the development of several re-melting and refining techniques to fulfill specific melting and refining requirements [6,12–15]. The obtained cast ingots are with homogeneous microstructure, without defects (segregation of the components, pores, etc.). They have uniformly distributed inclusions without high dispersion, better performance characteristics, and magnetic and resistance properties. The weight of the obtained samples varies from a few grams (such as pure metal tablets) to ingots, weighting up to 5–25 tons, necessary for the production of large components for the aerospace equipment, shipbuilding, nuclear reactors, aircrafts and other industries.

Tantalum, titanium, molybdenum, tungsten, niobium, zirconium, hafnium, ruthenium, platinum, vanadium (refractory and reactive metals) and their alloys [11,14,15,16–26], as well as copper, some steels, gold, nickel, aluminum and precision alloys based on cobalt and nickel or including rare earth components are produced by electron beam melting [7,15,27,28]. Despite its application in melting and refining of refractory and reactive metals and their alloys and in manufacturing of ultrapure sputtering target materials and electronic alloys [19,22], the EBM has an important role in the metal scrap recycling [7,29] and in the purification