

A three-dimensional steady state thermal fluid model of jumbo ingot casting during electron beam re-melting of Ti–6Al–4V



X. Zhao^a, C. Reilly^b, L. Yao^{b,*}, D.M. Maijer^b, S.L. Cockcroft^b, J. Zhu^b

^a Department of Mechanical Engineering and Materials Science, 301A Hudson Hall Engineering Building, Durham, NC 27708-0300, USA

^b Department of Materials Engineering, University of British Columbia, 309-6350 Stores Road, Vancouver, BC V6T 1Z4, Canada

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ABSTRACT

A 3-D coupled thermal-fluid model describing mass, momentum and energy transport within a Ti–6Al–4V rolling ingot cast in an (Electron Beam Cold Hearth Remelting) EBCHR process has been developed to describe steady state casting conditions. The model incorporates a number of the physical phenomena inherent to the industrial process, including a metal inlet in the center of one of the narrow faces, complex boundary conditions based on industrial practice, buoyancy driven flow within the liquid and flow attenuation using a Darcy momentum source term within the mushy zone. The model ignores turbulence in the liquid pool and Marangoni (surface tension) driven surface flows. The model has been validated against liquid pool depth and profile measurements made on an experimental casting seeded with insoluble dense markers and doped with dense alloy additions. Comparisons have also been made to video images taken of the top surface during casting. The results indicate that the model is able to quantitatively predict the steady state sump depth and profile and is able to qualitatively predict aspects of the top surface temperature distribution. The model has also been used to conduct a process heat balance and sensitivity analyses. The process heat balance conducted on the model domain indicates that at steady state the liquid metal inlet contributes 88% of the total power input, while the electron beam provides net 12% after accounting for radiation losses from the top surface; 62% of the heat is lost through the ingots sides and the balance is lost via bulk transport of sensible heat through the bottom of the domain. The results of the sensitivity analysis on pool depth indicate that casting rate has the largest effect followed by metal inlet superheat. The thermal, flow and pressure fields predicted by the steady state model serves as the initial conditions for a transient hot-top model, which is the subject of a forth-coming paper.

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1. Introduction and background

Prior to further downstream processing, virgin titanium sponge and scrap must first be melted and cast via a primary consolidation process. Two melting processes are employed industrially: vacuum arc remelting (VAR) and cold hearth melting (CHM). The latter includes both Electron Beam Cold Hearth Remelting (EBCHR) and Plasma Arc Remelting (PAR or PAM). In addition to functioning as a basic consolidation step (melting and casting) these processes are used to refine the alloy both in terms of adjusting alloy chemistry and eliminating unwanted and potentially deleterious constituents originating from the feedstock.

* Corresponding author. Tel.: +1 6049109220.

E-mail address: yaolu@mtrl.ubc.ca (L. Yao).

In the case of the EBCHR process, the focus of this study, particulate and partially consolidated material (including both virgin sponge and scrap) or material in ingot form is charged into a furnace at one end where it is melted by an electron beam (EB). An example configuration of an EBCHR furnace is shown schematically in Fig. 1. Generally 4–6 EB guns are used to melt the feed material, keep the metal molten as it transits from the refining hearth (crucible), and ensure the top of the cast ingot remains liquid. The various hearths and mold are constructed from water-cooled copper. The entire melting and casting operation is conducted within a vacuum environment, which typically ranges between 0.13 and 4 Pa, depending on the melt rate and volatile content of the material being melted. The casting process is semi-continuous, with lengths up to ~ 10 m, and a variety of ingot formats (cross sections) may be cast, unlike in the VAR process which is limited to round cross sections). The so-call “jumbo” ingot format, the subject of this paper, is used to produce ingots for conversion to plate and sheet mill products.

The main chemistry related defects found in primary melted titanium can be broadly group into two types: High Density Inclusions (HDI's) and Low Density Inclusions (LDI's). Both HDI's and LDI's can act as crack initiation sites in aero-engine disk material, hence there has been considerable work aimed at optimizing the refining capabilities of the EBCHR process from the standpoint of avoidance of these defects. In terms of defects arising in the casting process, there are primarily three: (1) segregation related defects, which plague certain combinations of alloy chemistry and ingot size; (2) void formation in the top of the ingot; and (3) chemistry deviations in the top of the ingot. The latter two form during the final transient stage of the casting process when the input of material to the mold has been suspended.

The majority of the EBCHR process models have focused on understanding the cold hearth and linking its operation to evaporative losses and inclusion removal. Tripp et al. [1] proposed a three-dimensional model to predict the depth of the liquid metal in the cold hearth. Westerberg et al. [2] studied the volatilization of aluminum during the melting of a titanium alloy in an axisymmetric crucible. Powell et al. [3] predicted aluminum losses during EBCHR of Ti–6Al–4V based on interface-reaction-controlled kinetics through the application of the Langmuir equation [4]. Ivanchenko [5], Akhonin et al. [6], and Semiatin et al. [7] implemented the Langmuir equation within one-dimensional diffusion models for the prediction of melt losses during EBCHM of alpha/beta titanium alloys. Bellot and co-workers [8] developed a three-dimensional thermophysical model of the cold hearth of the EBCHM process to predict aluminum volatilization and inclusion removal.

Looking first at the broader field of aluminum and steel production, models in the format of rolling ingots have been developed aimed at eliminating defects in the Direct-Chill (DC) casting of aluminum alloys [9,10] and continuous casting of steel [11]. Depending on the nature of the defect under investigation, these models have included thermal and stress analyses [9,10] or thermal and fluid flow analyses [11]. While this previous work serves as a good foundation for the present work – e.g. similar cross sections and semi-continuous in the case of DC casting of aluminum – there are significant differences. Most notably in the EBCHM process: (1) an electron beam continuously heats the top of the ingot in order to off-set high radiation losses and keep the material liquid; and (2) the casting process is carried out in a vacuum, which has a significant bearing on the heat transfer processes.

In terms of VAR processing of titanium alloys a number of studies have been completed by Jardy et al. [12–14] as part of the SOLAR program, which included the coupling of the thermal, electromagnetic and fluid flow fields. Here too there are notable differences; namely, the input of power to the top surface and the absence of electromagnetically induced forces in the EBCHR process (additionally, as previously mentioned the VAR process is limited to a cylindrical format – round ingot).

In terms of the casting process associated with EBCHR, a coupled thermal flow model was developed by Lesnoj et al. [15] for round ingot using an asymmetric analysis. Shyy et al. [16,17] have conducted two mathematically based studies discussing the effect of casting speed and gravity on pool depth and shape in EB cast Ti–6Al–4V round ingot during steady state

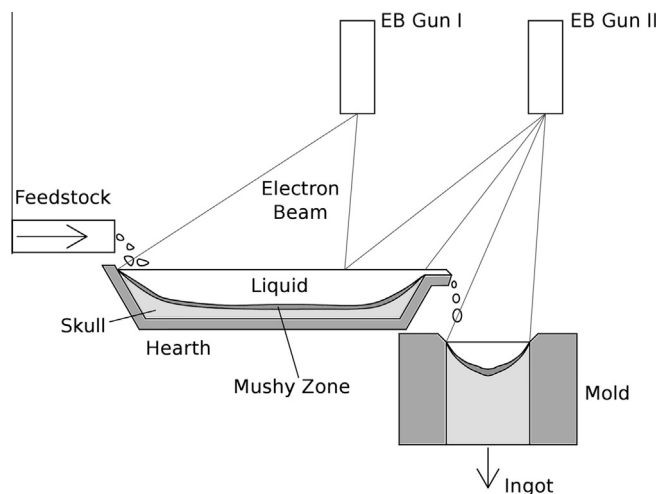


Fig. 1. Schematic illustration of the electron beam melting and casting process.

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