Simulation of Flow Field and Particle Trajectory in EB Cold Hearth Melting Process

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Abstract

Electron beam cold hearth melting process is an efficient method to produce the premium quality titanium alloys, especially to eliminate inclusions. A simulation work was carried out to study the process, concerning the flow field and particle trajectory at three different melt rates. The simulation results show that, when there is an overheat zone near the outlet zone, the molten metal flows to the sidewall of the cold hearth, and from the outlet zone to the inlet zone at the top surface which avoids the inclusion particle flows out the cold hearth. At the bottom of the liquid pool, the fluid flows to the outlet directly along the center plan, which forms a short circuit, decreases the residence time of the inclusion particles; there is a critical density range of inclusion particles, which have more probability to flow out of the cold hearth. The inclusion particles, whose density lower than it, will flow to the sidewall. The inclusion particles, whose density higher than it, will sink into the bottom mushy zone. Both cases let the inclusion have higher probability to eliminate the inclusions.

Introduction

Titanium alloys are mainly used in the aero and space industry due to there high specific strength and high corrosion resistance. From the beginning, the hard alpha inclusions, which are brittle, were found in the alloys. The existence of this kind of inclusions can decrease the component low cycle fatigue property because they can be the crack source. In the early 90's of 20 century, the EBCHM (Electron Beam Cold Hearth Melting) process was used to produce the premium quality titanium alloys[1-5]. As a new technology instead of the VAR (Vacuum Arc Remelting) process, the EBCHM process separates the melting process into three different zones: raw material melting zone, refining zone and solidifying zone. The melt rate, the power input and the power distribution can be adjusted flexibly, which lets the molten metal temperature and the molten metal residence time in the cold hearth to be easily controlled, which are the critical variables. These are the important advantages to eliminate the inclusions in the raw material.

The inclusions can be removed by the following mechanisms: (1) rise to the high temperature surface layer, and dissolved there; (2) flow with molten fluid, and dissolved in fluid; (3) density sink to the bottom mushy zone, attached or dissolved there. At high temperature, the fluid flow and the temperature are difficult to determine. Many researchers have investigated the dissolution rate of the hard alpha inclusion in selected titanium alloys, also some mathematical simulation works in the cold hearth have been done. But the detailed flow field and particle trajectory and residence time in the cold hearth were not reported.

The mathematical simulation method is an available and economical method to investigate the molten metal and inclusion behavior in the cold hearth. In the current study, the relationship among fluid flow, inclusion motion, and melt rate was investigated.

Mathematical Model and Simulation Parameters

The important point to carry out a reliable mathematical simulation is the choice of a suitable turbulence model[6]. The choice of turbulence model will depend on considerations such as the physics encompassed in the flow, the established practice for a specific class of problem, the level of accuracy required, the available computational resources, and the amount of time available for the simulation. Here, the k-ε Reynolds averaging method was selected. The finite volume method was used to calculate the conservation equations. The dimension of the simulated cold hearth is 500×300×72mm, the top surface is divided into 5 zones(shown in fig.1): the inlet zone, the main heating zone, the overheat zone, the no heat zone and the zone below feeding bar. Due to the symmetry, only half of the cold hearth was simulated. Table 1 gives the parameters used in the simulation. Three different melting rates were simulated. The convergence is adjudged when the heat flux balance less than 100W.
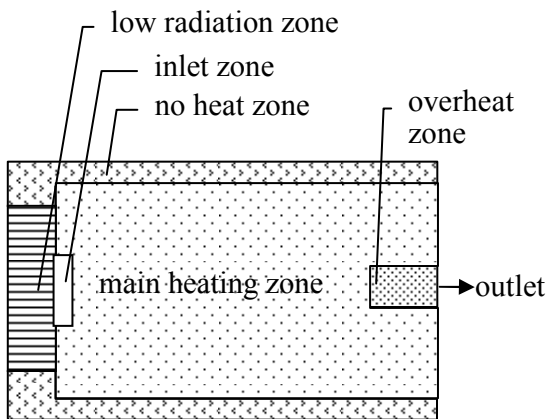
Figure 1. Different zones on the top surface of cold hearth.

Table1. Simulation parameters of liquid Ti64.

Parameter	Value	Units
density	$4055\times(1-6.69\times10^{-5}\cdot(T-1898))$	kg/m^3
thermal conductivity	30	W/m·K
thermal capacity	700	J/kg·K
dynamic viscosity	$0.2153\times10^{-3}\exp(10307/(1.987T))$	Pa·s
solidus	1868	K
liquidus	1898	K
emissivity	0.2	W/m^2·K^4
Inlet temperature	1998	K

Simulation Results and Discussion

Temperature Distribution In The Cold Hearth

The surface temperature distributions at different melting rate are shown in Figure.2. From Figure.2 a) to c), the temperature in the outlet zone is about 2190K, and obviously higher than the other zones because of the more power. The temperature at the main zone is between 2000K and 2050K. In fig.2 d), the overheating zone near the outlet zone is deleted, so the highest temperature point is near the center of the cold hearth.

Flow Distribution In The Cold Hearth

The flow distributions at different melt rate are shown in Figure.3. From Figure.3 a) to c), the surface molten metal flows from the outlet zone to the inlet zone, and from the center zone to the side wall. This is because the buoyancy force caused by the temperature, so the liquid titanium alloy flows from the high temperature zone to the low temperature. In Figure.3 d), there is no overheat zone near the outlet zone, so the molten metal flows away from the center of the cold hearth. In Figure.3 e), the liquid titanium alloy near the bottom mushy zone flows from the inlet zone to the

outlet zone. Part of the liquid titanium alloy flows up to the top surface, and then flows back to the inlet zone.
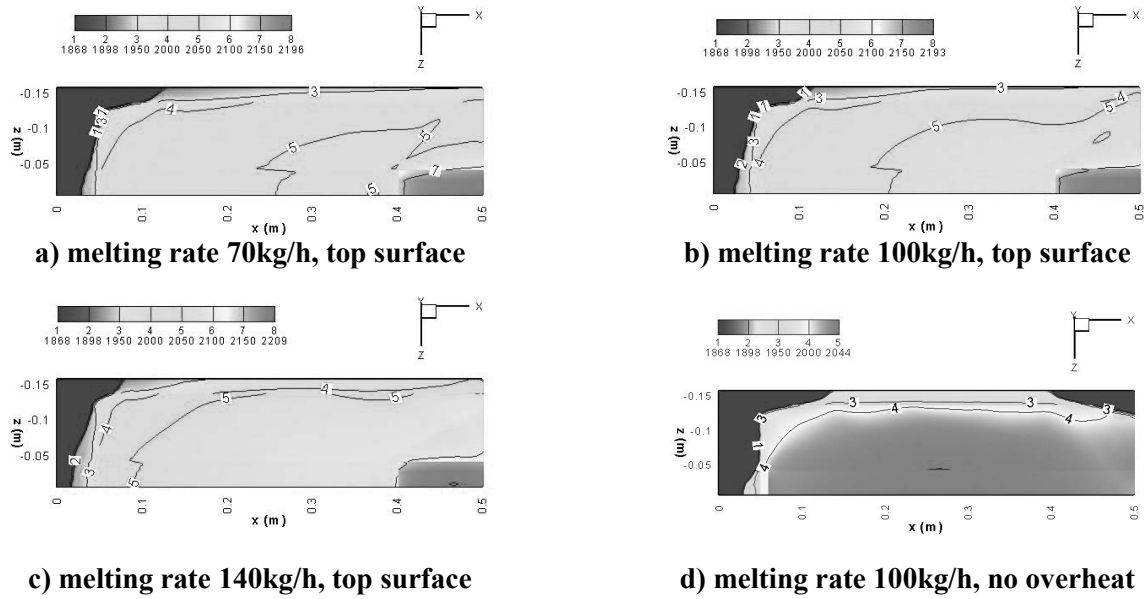

a) melting rate 70kg/h, top surface

b) melting rate 100kg/h, top surface

c) melting rate 140kg/h, top surface

d) melting rate 100kg/h, no overheat

Figure 2. Temperature distribution in cold hearth.

a) melting rate 70kg/h, top surface

b) melting rate 100kg/h, top surface

c) melting rate 140kg/h, top surface

d) melting rate 100kg/h no overheat, top surface
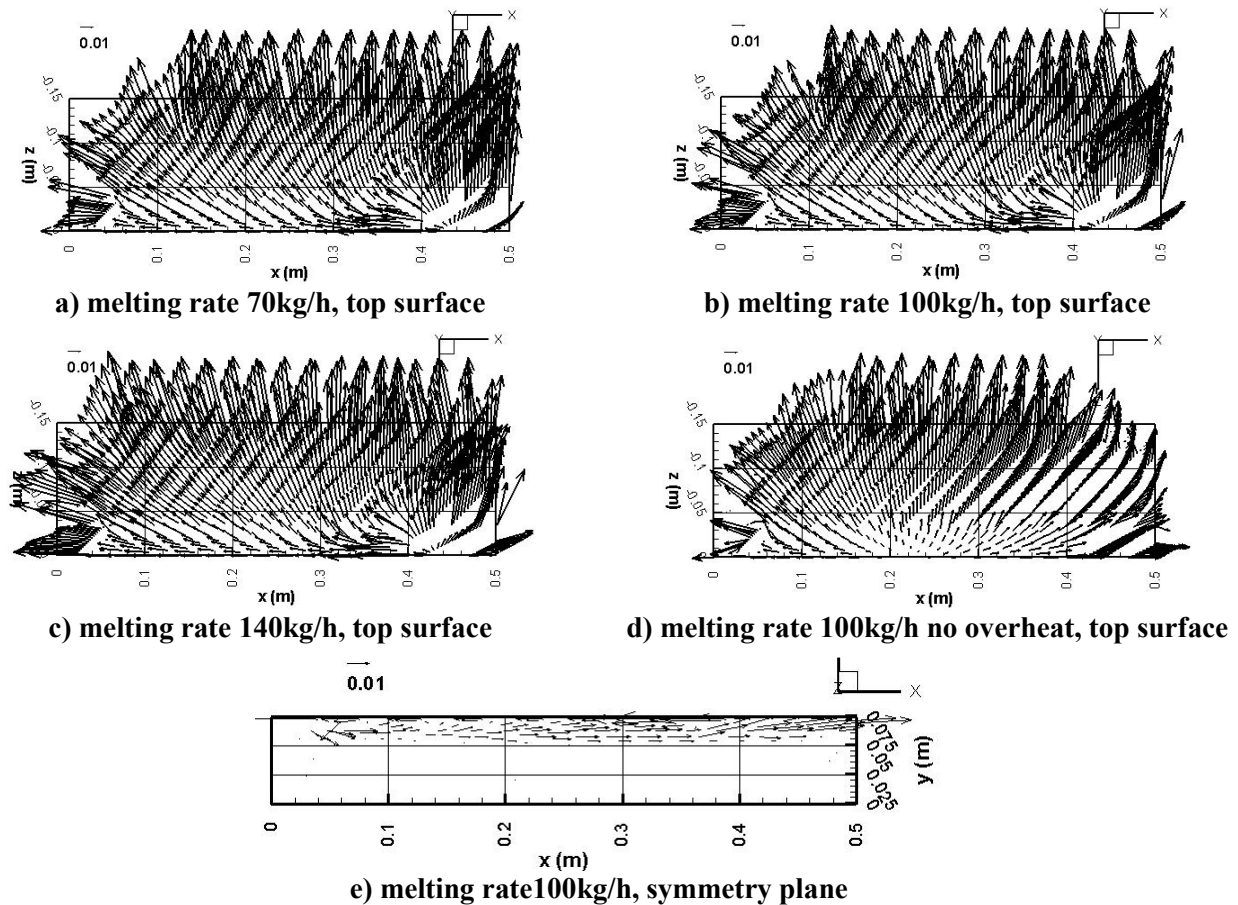

e) melting rate100kg/h, symmetry plane
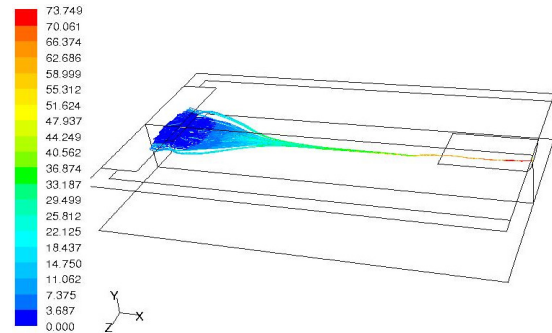
Figure 3. Flow distribution in cold hearth.

Particle Residence Time In The Cold Hearth

Fig.4 shows the residence time of the particles of different densities and diameters when they are added evenly in the inlet zone. The density of particles between $4030kg/m^3$ and $4070kg/m^3$ is a

critical density range, which have more probability to flow out of the cold hearth. The shortest time to the outlet zone is about 60 seconds. The particles with density higher than the critical range will sink down to the bottom, adhere to the mush zone, and flow very slowly. There time to arrive to the outlet zone is more than 10 minutes. The particles with density lower than the critical zone will flow up to the high temperature top surface, and flow back to the inlet zone or the side wall. They also need more than 10 minutes to flow out the cold hearth. The flow trajectory of the particle (particle size 0.001m, density 4050kg/m^3) at melt rate 100kg/h is shown in Figure. 5.
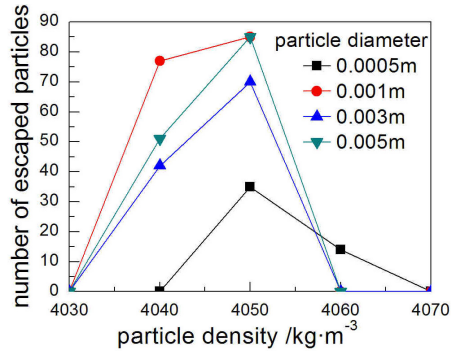
Figure 4. Relation between escaped particle number and particle density.

Figure 5. Particle trajectory at melt rate 100kg/h, particle size 0.001m, density 4050kg/m^3.

Conclusion

From the simulation result, during EBCHM process, the melting power distribution in the cold hearth substantially influences the temperature distribution, the flow distribution, and the inclusion elimination ability and can be optimized. But there is a critical density range of particles to flow from the inlet zone directly to the outlet zone, this problem should be pay more attention and may be solved by the cold hearth design optimization.

Acknowledgement

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