Multiscale Simulation of the Effect of Axial Magnetic Field on Macrosegregation and Solidification Structure During Vacuum Arc Remelting of TC17

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Abstract: The effects of axial magnetic field on the macrosegregation and microstructure in vacuum arc remelted ingots of titanium alloy TC17 are investigated by a multiscale modelling approach which combines macroscale transport model with a mesoscale cellular automation model. The results show that with the increase in the intensity or reversal time of the axial magnetic field, the enhanced melt swirl drives a stronger second flow in the vertical plane, which is downward along the sidewall of melting pool and upward in the centerline. When such flow in vertical plane evenly matches with the flow driven by the self-induced Lorentz force, the macrosegregation in the ingot is the weak. Moreover, it is found that the columnar grain structure changes to fine equiaxed grain with the increase in the in the intensity or reversal time of the axial magnetic field.

Keywords: Vacuum Arc Remelting, macrosegregation, solidification, grain structure.

1 Introduction

The Vacuum Arc Remelting (VAR) process is extensively used to produce high quality alloys such as titanium, zirconium and nickel-based alloys. During the VAR process an axial magnetic field (AMF) generated by external induction coils is deliberately introduced to confine the arc under the electrode. The interaction of AMF with the melting current gives rise to a stirring Lorentz force, which induces melt swirl in azimuthal direction. It is usually recognized that a unidirectional stirring will deteriorate the ingot quality. So the AMF is reversed periodically. The reversal time and intensity of AMF influence the melt flow and solidification, thus determine the quality of ingot. In recent years such topic has been explored by several numerical studies [1-5]. Spitans et. al. [1] and Karimi-Sibaki et. al. [2] performed simulations to reveal the complex flow behavior induced by the competition between the self-induced magnetic field and time-varying AMF. But the solute transport is absent in these works and thus there is no results about macrosegregation. Cui et. al. [3] and Han et. al. [4] detected the intensity of AMF on the macrosegregation during the VAR of Ni-based alloy and Ti_2AlNb alloy, respectively. They found that the application of AMF can reduce the macrosegregation. But with further increase in the intensity of AMF this effect becomes limited [3] or even results in more significant segregation [4]. It should be mentioned that the reversal time of AMF in these two studies are fixed. By using cellular automation (CA) simulation, the difference in grain structure between situations with and without AMF were revealed by Atwood [5]. Although these fantastic studies have given some insights into the effects of AMF, present understanding of the relations between the parameters of AMF and the ingot properties, such as macrosegregation and grain structure, are still limited. Here we investigate how the intensity and reversal time of AMF affect VAR ingot qualities by a multiscale modelling approach.

2 Experimental procedure

The model for macroscale transport was based on the continuum mixture model for alloy solidification, extended to incorporate electromagnetic field. Details could be found in our previous paper [6]. A 2D axisymmetric model was developed for the TC17 (Ti-1.97Zr-3.85Mo-3.9Cr) VAR ingot with diameter of 680mm and height of 1920mm. The temperature predicted by the macromodel was passed into the CA model for the grain growth simulation. The grid size and time step used in macroscale were 10mm and 0.1s, both of which were ten times larger than those in mesoscale. Therefore, the macroscale temperature field were bi-linear interpolated in space and linear interpolated in time to obtained the mesoscale distribution.

3 Result and discussion

The final distribution of Zr in the ingot in different AMF conditions are shown in Fig. 1. It can be seen from Fig. 1 (a)-(c) that the positive segregation in the center region decreases slightly as the intensity of AMF increases from 10 GS to 30 GS, and then with the further increase of AMF to 90G both the positive segregation in the center part and negative segregation in the periphery of the bottom region enhance. This founding is consistent with the reported results in reference [4]. The effect of reversal time can be found by comparing the results in Fig. 1(a), (d) and (e). It can be seen that the macrosegregation become seriously as the reversal time increases from 16s to infinite (no reversal of AFM). The segregation of Mo and Cr exhibits similar variation trend with the intensity and reversal time of AMF.

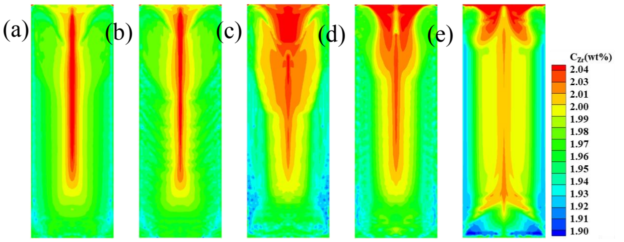

Figure1 Thel distribution of Zr in different AMF conditions (a)10GS-8s, (b) 30GS-8s , (c) 90GS-8s , (d) 30GS-32s , (e) 30GS-infinite

The macrosegregation is determined by melt flow, which is shown in Fig. 2. The left side of each figure is the velocity vector in the vertical plane and the right side is the distribution of swirl velocity. It can be found from Fig. 2(a) that the swirl velocity increases with the intensity of AFM. The enhanced melt swirl drives a stronger second flow in the vertical plane (the so-called Ekman pumping), which is downward along the sidewall of melting pool and upward in the centerline. When AFM gets to 30 GS, Ekman pumping is evenly match with the flow driven by the self-induced Lorentz force, thus the macrosegregation in the ingot is weak. The effects of AFM reversal time on the melting pool shape and flow can be seen in Fig. 2(b). The melt flow along sidewall is enhanced as the reversal time increases to 64s, thus more solute enriched liquid transports to the bottom of melting pool, which results in an enhanced segregation. When the reversal of AFM is stopped, the mushy zone of melt pool enlarges significantly, which results in more serious segregation.

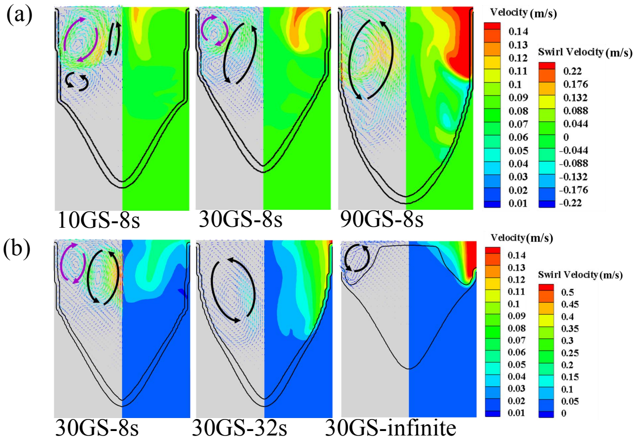

Figure2 Velocity vector(left) and swirl magnitude (right) for various (a) AFM intensity and (b) AFM reversal time.

The final grain structures in different AMF conditions are shown in Fig. 3. As can be seen, both the increase of AFM intensity and lengthening of reversal time can enlarge the equiaxed grain zone and refine grain structure.

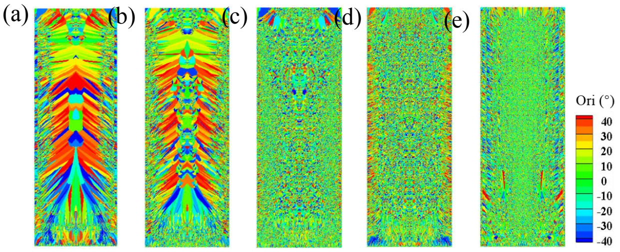

Figure3 The grain structures in different AMF conditions. (a)10GS-8s, (b) 30GS-8s , (c) 90GS-8s , (d) 30GS-32s , (e) 30GS-infinite

4 Conclusion

With the increasing in the intensity or reversal time of AFM, the swirl and Ekman pumping flow is enhanced, which can weaken the flow dirven by the self-induced Lorentz force. The macrosegregation is weak in moderate intensity of AFM, but is enhanced without reversal of AFM. The increase of Lorentz force and lengthening of reversal time can enlarge the equiaxed grain zone and refine grain structure.

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