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Dimensionless parameters controlling fluid flow in electromagnetic cold crucible

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ABSTRACT

A 3-D numerical model was established for predicting the flow field in a square electromagnetic cold crucible (EMCC) used for melting and directionally solidifying TiAl alloys. Four dimensionless parameters that characterise the melt flow in the EMCC were derived, those being the Hartman (Ha), magnetic Reynolds (R_ω), coils-melt position (h) and the ratio of the melt height to length (H/L) numbers. Parametric simulations and experiments were carried out to understand the effects of processing parameters such as the intensity and frequency of the current, the relative coils-melt position and the melt shape on the flow field. The meridional flow normally consists of two vortices in the half meridian plane, the lower vortex decreases with increasing Ha, R_ω and h ($h_b > h_m$), as well as decreasing H/L. Higher Ha, H/L and lower h induce intensive fluid flow in the melt due to the stronger EM coupling, which could promote the uniformity of solute in the melt. The turbulence kinetic energy is significantly influenced by the length scale of the turbulent flow and the flow velocity in the melt, it increases with increasing Ha, h and H/L, while reduces and tends to be stable at higher R_ω. Relatively higher flow velocity and turbulence kinetic energy can be obtained when R_ω is close to 10. The weakened flow in the vicinity of solid/liquid interface under lower Ha and R_ω, as well as higher h and H/L is beneficial for continuous growth of columnar crystals during the directional solidification process.

1. Introduction

Both steady and non-steady magnetic fields are efficient ways to control the fluid flow in the melt, and many beneficial effects have been observed at the crystallization of eutectics, high-temperature superconducting compounds and organic crystals. Wang et al. (2016) used a steady magnetic field during the high speed gas metal arc welding process, and found that the electromagnetic force could reduce the maximum and the average longitudinal velocity in the weld pool. Wei et al. (2017) applied a permanent magnetic stirring (PMS) facility to investigate the influence of PMS on solidification of Al-4Cu and 2024 Al, and the results indicated that the PMS can effectively refine grain structures of these alloys. The high frequency electromagnetic field is widely used in the melting and solidification process, which leads to effective heat and mass transfer in the melt. Li et al. (2016) have reported that the electromagnetic stirring could effectively refine the grain size of AZCa912 alloys with the finest grain size of about 120 μm in average diameter. Dong et al. (2016) numerically investigated the effects of structural design and transport process parameters on electromagnetic transport (EMT) for high pressure die casting, their investigations realized the optimal EMT process with low cost, high transport efficiency and stationarity. Sheikholeslami et al. (2017) reported that the magnetic field induced flow significantly influenced the mass and heat transfer behaviors in nanofluid, which was suggested as a new passive way for heat transfer improvement.

Based on the induction skull melting and continuous casting technique, Fu et al. (2008) first proposed the cold crucible directional solidification (CCDS) method for directionally solidifying TiAl alloys with controllable microstructure and no contamination. During the process of CCDS, the coils with high frequency alternating current induce electromagnetic field and eddy current in the charge. The schematic of the electromagnetic cold crucible (EMCC) used for melting and directional solidification, as well as the typical flow field in the meniscus are shown in Fig. 1.

The electromagnetically driven flow is essential for convective heat and mass transfer during crystal growth, and a higher flow velocity leads to the reduction of both the radial temperature and concentration gradients in front of the solid/liquid (S/L) interface. Hachni et al. (2015) reported that the forced convection driven by a traveling magnetic field could effectively reduce macrosegregations and promote equiaxed structures. Generally, the fluid flow driven by high frequency electromagnetic field in the cold crucible is very complicated due to the

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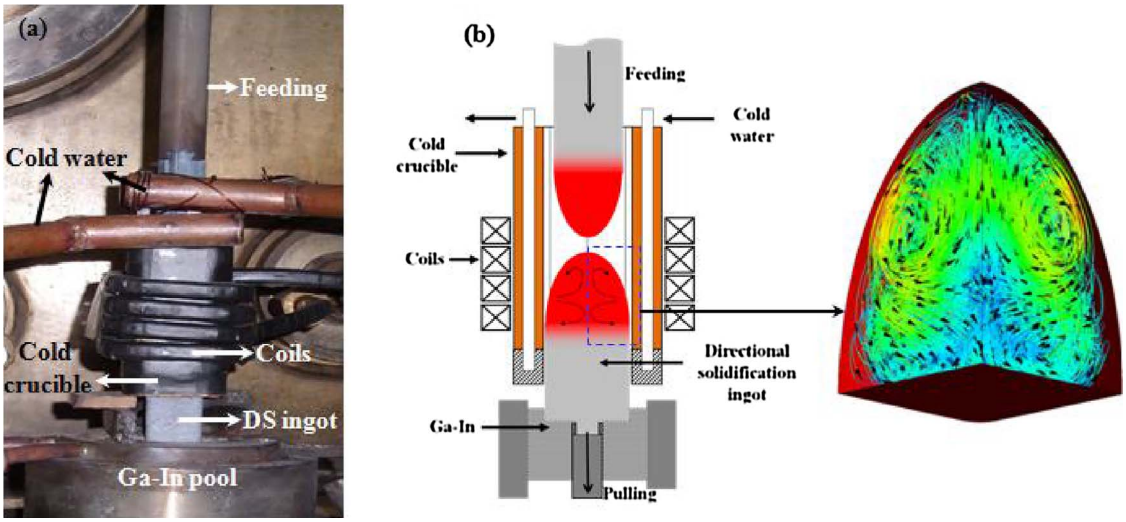

Fig. 1. Cold crucible directional solidification process (a) equipment and installation, (b) schematic of the EMCC and the flow field in the meniscus.

turbulence and various physical effects that occur in the melt. Umbrashko et al. (2006) revealed that the electromagnetically driven flow in the induction finance is turbulent and the amplitude of the oscillating velocity part is comparable with the characteristic velocity magnitude. Scepanskis et al. (2012) proved that the most intensive oscillating convection is located near the crucible wall between the main vortices. Dropka et al. (2013) pointed out that in the case of a longitudinal alternating magnetic field, the turbulent flow could deplete the diffusion boundary layer. There is an increasing trend towards investigations of melt flow with a square cross-section. Taniguchi and Brimacombe (1994) proved that different configurations could affect the efficiency of mass transfer, the rectangular pipe with secondary flow generated in the cross section of the square pipe has higher efficiency.

A successful concept of microstructure control requires an improved knowledge with respect to the details of the fluid flow in the melt during directional solidification by the EMCC. A 3-D model was established to calculate the fluid flow in a square EMCC under various processing parameters, and four dimensionless parameters were derived to analyze the characteristics of the fluid flow in the melt, those being the Hartman, magnetic Reynolds, coils-melt position and *H*/*L* numbers.

2. Experimental procedure

2.1. Melting of TiAl alloys

The Ti-48Al alloy was first melted in a square EMCC, then the tungsten (W) particles with sizes of 5–10 μm were dropped on the surface of the meniscus. It is easier for the W particle to enter into the melt from the surface due to its higher density (19350 kg/m^3). After the W particles have been mixed in the melt for a time, the melt was quenched into the liquid Ga-In pool to restore the molten pool with W in it. The TiAl melt was quickly solidified and the dendrite/equiaxed grains with dissolved W grew in the melt. As the element W is a stronger β-stabilizer, the β phase with high-W containing could be retained at low temperature and subsequently transform to B2 phase at room temperature. The B2 phase is a bright phase in BSE mode and is easy to be recognized for identifying the distribution of W in the melt. The distribution and concentration of W in the molten pool was investigated by scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS).

2.2. Directional solidification of TiAl alloys

The as-cast TiAlNb ingots were prepared by induction skull melting technology and remelted three times for homogenization. Then the ingot was cut into many smaller bars (Φ20 mm) as the primer and feeding rod. Directional solidification experiments were carried out under a certain pulling velocity and different coil powers in a square EMCC, as shown in Fig. 1. The directionally solidified TiAlNb ingots were cut into two halves longitudinally for macro/microstructure observation. The samples were prepared using standard metallographic techniques and etched in a modified Kroll's reagent. The macrostructure of the ingots was photographed using a Nikon D7000 Digital Single Lens Reflex.

3. Mathematical model description

3.1. Geometry definition

As shown in Fig. 2, a 3-D model of the square EMCC and the mesh were generated using ANSYS (distributed by ANSYS HIT) according to the experimental equipment. Only a quarter of the square EMCC was established due to the symmetry of the square EMCC. As presented in Fig. 2(c), the meniscus with planar S/L interface composes the computational domain of fluid flow. The fluid zone was discretized using tetrahedron and hexahedron elements, and there were 306,409 elements in the whole domain for solving the electromagnetic field by ANSYS and 961,512 elements in the meniscus domain for solving the flow field by Fluent. The material properties for magnetic field and flow field calculation are shown in Table 1.

3.2. Derivation of dimensionless parameters

It was assumed that the liquid metal is non-magnetic with large electrical conductivity. The high frequency electromagnetic field in the charge is limited to the skin layer due to skin effect, its thickness, δ, depending on the coils current frequency ω,

$$\delta = \sqrt{\frac{2}{\mu\sigma\omega}} \tag{1}$$

In order to reflect the interaction of the high frequency electromagnetic field with the melt, the magnetic Reynolds number, R_ω, it is the square of the ratio of the sample radius to the thickness of the skin layer,