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Experimental and numerical investigation on mass transfer induced by electromagnetic field in cold crucible used for directional solidification

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ABSTRACT

Electromagnetic stirring induced by alternating magnetic fields could generate complex mass transfer in the liquid metals. In this paper, the flow field and the mass transfer behavior induced by the high frequency magnetic field in a square electromagnetic cold crucible (EMCC) used for directional solidification was experimentally and numerically investigated. By using tungsten particles as the tracer, the experiments under different operating powers and times were carried out, and the distribution of the particles in melt after cooling were analyzed. The results show that two mean eddies exist in the half meridian plane of the molten pool, and the skin effect results in a stronger convection within the skin layer. The mass moves following the mean eddies and emerges preferentially in the skin layer; when the mass is transported to the region between the upper and the lower eddies, which is homogenized in axial by the strong oscillations of convection. However, there is a concentration gradient along the radial in melt due to the skin effect. It found that the mass distributes more uniform with higher operating power or longer time. Moreover, the inhomogeneous convection at the vicinity of solid-liquid interface leads to the heterogeneous distribution of the mass, which aggravates the deflection of solid-liquid interface and changes the phase transition path during crystal growth.

1. Introduction

Magnetic field is widely used in the solidification process to improve the microstructure and mechanical properties of materials [1–4], as well as the heat and mass transfer [5–7]. Based on the induction skull melting and continuous casting technique, the cold crucible directional solidification (CCDS) was first proposed by Fu et al. [8] for directional solidifying refractory and active alloys with controllable microstructure and low contamination. During the process of CCDS, a bottomless electromagnetic cold crucible (EMCC) encircled with coils is used for melting and heating materials, while longitudinal temperature gradient in the melt is formed due to intensive cooling by the Ga-In liquid pool at the bottom. The coils with high frequency alternating current (AC) generates magnetic field (B) and induces alternating current (J) in the conductive metals [9]. Due to the skin effect, the B and J are confined to a thin layer, where the induced current causes Joule heat in the metals to melt and overheat, and the interaction of B and J results in Lorentz force to stir and shape the liquid metals. The confined meniscus and concentrated Joule heat in skin layer reduces and compensates the heat loss to the cold wall, which makes it possible to eliminate the radial thermal gradient during directional solidification.

In addition to the induction heating, knowledge of the convection induced by the Lorenz force is important. The forced convection driven by traveling magnetic field could effectively reduce macrosegregations during solidification [10], and the electric field, magnetic field induced flow significantly influence the mass and heat transfer behavior in nanofluid presented by Sheikholeslami et al. [11,12]. Generally, the flow field in the cold crucible is very complicated due to the turbulence and various physical effects happened in the melt. Owing to the harmonic nature of both electromagnetic (EM) field and induced eddy currents, the Lorentz force can be decomposed into a steady and harmonic part that oscillates with double frequency of EM field [13]. The flows of liquid induced by single-phase AC magnetic fields have been studied both theoretically and experimentally in many published papers [14–17]. Taberlet and Fautrelle [16] reported that the turbulence is non uniform and there is an increase in the turbulent fluctuations and dissipation rate, while a decrease of the integral scale within the thickness of skin layer at high frequency. The transient velocity measurements by Umbrashko et al. [18] revealed that the melt flow is unstable and the amplitude of the oscillating velocity part is comparable with the characteristic velocity magnitude. The most intensive of them are located close to the crucible wall

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Nomenclature

$\vec{B}$	magnetic flux density vector (T)	d_p	particle diameter (m)
$\vec{E}$	electric field intensity vector (V m^{-1})	C_D	drag coefficient
$\vec{J}$	current density vector (A m^{-2})	Re_p	Reynolds number of particle
$\vec{F}_{EM}$	Lorenz force vector (N m^{-3})	$\vec{F}_{pEM}$	volumetric Lorenz force on particles (N m^{-3})
Q	induction heat (J)	V_p	volume of the particle (m^{-3})
t	time (s)	f	interface deflection
C_p	specific heat of TiAl melt (J kg^{-1} K^{-1})	f_T	thermal interface deflection
k	thermal conductivity of TiAl melt (W m^{-1} K^{-1})	f_C	solutal interface deflection
Re	Reynolds number of fluid	m_L	liquidus slope (K wt.%$^{-1}$)
L	characteristic length scale of fluid flow (m)	C	concentration of solute in the melt (wt.%)
$\vec{v}$	velocity vector of melt (m s^{-1})	G_T	conductivity-weighted temperature gradient (K m^{-1})
$\vec{v}_s$	velocity vector of interface (m s^{-1})		
$\vec{v}_p$	velocity vector of the particle (m s^{-1})	*Greek symbols*	
n	surface normal vector	σ	electrical conductivity of melt (S m^{-1})
p	pressure (N m^{-2})	σ_p	electrical conductivity of particle (S m^{-1})
q_{ra}	radiative heat of TiAl melt (J)	υ	dynamical viscosity (kg m^{-1} s^{-1})
q_{hf}	heat flux (J)	σ_0	Stefan-Boltzmann constant (5.76×10^{-8} W m^{-2} K^{-4})
h	coefficient of thermal conductivity (W m^{-2} K^{-1})	ρ	density of melt (kg m^{-3})
T_s	free surface temperature (K)	ρ_p	density of particles (kg m^{-3})
T_∞	ambient temperature (K)	ε	emissivity
$T_{Ga\text{-}In}$	temperature of *Ga-In* liquid pool (K)	μ	permeability of fluid (H m^{-1})
T	temperature of ingot (K)	δ	skin layer thickness (m)
F_D	drag force (N m^{-3})	ω	angle frequency (rad s^{-1})

between the main vortexes, which has been proved by Kirpo et al. [19] and Scepanskis et al. [20]. The studies show that a complicated flow field could be induced by the high frequency AC, which will play a main role in convective heat and mass transfer.

Lots of investigations have proved that the melt flow in the molten pool could affect the solute distribution that determine the solid microstructure. Fautrelle et al. [21] found the thermoelectric magnetic (TEM) flows at the vicinity of solid-liquid interface can transport the rejected solutes from the depressed region of interface to the protruding region, which can decrease the interface tilting degree. Bogno et al. [22] revealed the lateral solute segregation induced by the fluid flow results in a significant deformation of the solid-liquid interface, moreover, the fluid flow can also influence the growth velocity and the characteristic parameters of the solute boundary layer. In addition, the transverse solute gradient in front of the solid-liquid interface gives rise to a transverse microstructure gradient, as already shown in the previous papers [23,24]. The bottomless EMCC for directionally solidifying active and refractory alloys for industrial applications has been proposed but no experimental work was reported on the mass transfer in melt. The main purpose of our investigation is to study the flow field driven by high frequency electromagnetic field in a square cold crucible, in particular, its influence on the mass transfer behaviors in the melt and on the solid-liquid interface. The experiments and simulations were carried out under different operating powers and times, and the mass distribution in melt after cooling were analyzed. It is expected that the results reported in this paper can be used as a guideline for those who are interested in the mass transfer behaviors during melting and directional solidifying active and refractory materials in the cold crucible under high frequency AC.

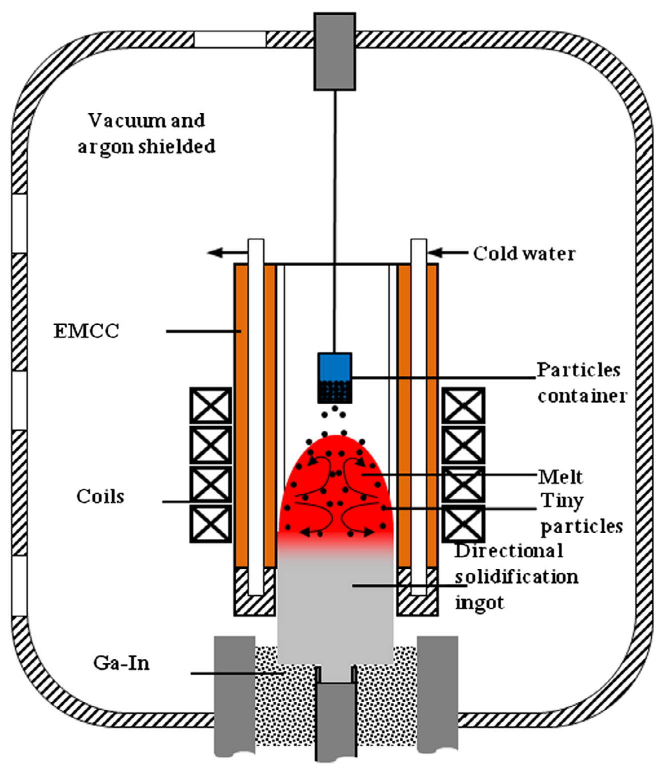

Fig. 1. Schematic diagram of the experiment process.

2. Mathematical models and experiments

2.1. Experimental technique

The schematic diagram of experiment process is shown in Fig. 1. A square EMCC with section size of 30 mm × 30 mm was used and the induction coil can supply with the power of 0–100 kW and the frequency of 30 kHz. The Ti-48Al alloy as the model liquid metal was melted and a molten pool was formed in the square EMCC by continuously increasing of operating powers. After that, the tungsten particles with size of 2–5 μm were dropped on the surface of meniscus and the time was recorded as t_0. The maximum solubility of W in TiAl alloy can reach as much as 1.2 at.% according